Bellcomm

955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

B71 10021

date: October 29, 1971

to: Distribution

from: J. J. Schoch

subject: Use of On-Orbit Propellant in Shuttle Orbiter for Tug Payload Increase - Case 237

## ABSTRACT

Three different ways of using the space shuttle orbiter abort propellant to increase the height of the parking, or space tug departure, orbit on an easterly mission to synchronous orbit were investigated. Calculations were based on a combined weight of tug and payload of 65000 lb and a fixed tug propellant fraction. An increase in payload of 600 lb above the payload of about 6800 lb obtainable with no on orbit propellant utilization is realized when the on orbit propellant is used to go into an intermediate 166 nm altitude circular orbit. Going into an intermediate 100 x 231 nm elliptical orbit provides a 1000 lb increase in payload. Deorbiting from apogee of an elliptical parking orbit brings the total payload increase to 3000 lb or a net increase of 44% above the 6800 lb payload realized by not utilizing the on orbit propellant.

(NASA-CR-126154) USE OF ON ORBIT PROPELLANT IN SHUTTLE ORBITER FOR TUG PAYLOAD INCREASE (Bellcomm, Inc.) 25 p

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# MEMORANDUM FOR FILE

## INTRODUCTION

On a 28.5 degree inclination easterly mission to a 100 x 100 nm orbit with 65,000 lb payload, the orbiter of the fully reusable two-stage shuttle has an on orbit $\Delta V$ capability of about 900 ft/sec of which 500 ft/sec is needed for deorbiting from the 100 nm circular parking orbit while the rest is a reserve for abort during ascent. Once the orbiter has reached the parking orbit, the abort propellant is not needed and may be used for other purposes. For instance, if the shuttle payload were to be a tug that goes to a synchronous orbit, the abort propellant could be used to raise the height of the orbiter parking orbit and thereby increase the tug payload. Three methods to implement this idea that have been analyzed will be described in more detail.

## MISSION MODES AND THEIR CHARACTERISTICS

The three different modes that were considered are shown schematically on Figure 1, 2, and 3. For clarity, departure and arrival orbits are kept separate. Going into an intermediate circular orbit is discussed first.

The upper part of Figure 1 represents the departure. The shuttle orbiter with the tug as payload is initially in a 100 nm circular orbit and it is represented by a heavy circle in the figure. Part of the on-orbit propellant is used to bring them into an intermediate circular orbit by making a Hohman transfer with $\Delta V_1$ and $\Delta V_2$. The orbiter remains in this orbit while the tug is brought to a synchronous orbit with an additional Hohman transfer including plane change represented by $\Delta V_3$ and $\Delta V_4$ ($\Delta V_4$ not shown on Figure 1). The return from the synchronous orbit is shown on the lower part of Figure 1. The empty tug goes back to the intermediate circular orbit by means of a Hohman transfer and plane change represented by $\Delta V_5$ (not shown) and $\Delta V_6$. After joining the shuttle orbiter the tug and the orbiter together are brought to the original 100 nm parking orbit by making a Hohman transfer $\Delta V_7$ and $\Delta V_8$ using some more orbiter on orbit propellant. Finally the orbiter with the tug deorbits, $\Delta V_9$, using the remaining on orbit propellant.

By going into an intermediate circular orbit, an additional $\Delta V$ over that required to go directly to synchronous orbit is required. This may be considered to be a penalty or loss. A detailed treatment of the $\Delta V$ loss resulting from intermediate circular parking orbit is given in Appendix 1. The results are given on Figure 4. $\Delta V$ losses are plotted vs the altitude of the intermediate circular orbit. Several final orbits lower than synchronous altitude are also plotted on this graph. If the final orbit has an altitude below 1500 nm, the losses caused by going into an intermediate circular orbit become insignificant. When going into a high orbit, for instance into a synchronous orbit, the losses caused by using an intermediate circular orbit are quite substantial. For example 120 ft/sec is lost by using a 200 nm altitude intermediate circular orbit, and almost 250 ft/sec is lost when the intermediate orbit is at 300 nm. High altitude intermediate orbits may cause losses of as much as 2000 ft/sec.

The second mode considers going into an intermediate elliptical orbit as represented on Figure 2. The departure is again given on the upper part of the figure. Initially both orbiter and tug are together on a 100 nm circular orbit (heavy line). The orbiter then uses part of the on orbit propellant to bring both vehicles into an intermediate elliptical orbit, $\Delta V_1$. While the orbiter remains in this elliptical parking orbit the tug, having made one revolution, starts at periapsis a Hohman transfer and a plane change to go into synchronous orbit $\Delta V_2$ and $\Delta V_3$ ($\Delta V_3$ not shown on Figure 2). When the empty tug returns from synchronous orbit by a Hohman transfer and a plane change $\Delta V_4$ and $\Delta V_5$ ($\Delta V_4$ not shown), it joins the orbiter on the intermediate elliptical orbit. Using some additional on orbit propellant, the orbiter effects a circularization maneuver at periapsis $\Delta V_6$ which brings the two vehicles into a 100 nm circular parking orbit from which they are then deboosted $\Delta V_7$ to an entry condition.

The use of an elliptical orbit as an intermediate orbit introduces no loss because the vehicle returns to the same perigee from which the first part of the Hohman transfer was executed. Consequently any $\Delta V$ expended to go into an intermediate elliptical orbit is subtracted from the $\Delta V$ of the subsequent Hohman transfer to synchronous orbit.

Reference is now made to Figure 3 showing a third mode. This mode is similar to mode 2 except that, after the tug returns from synchronous orbit and joins with the orbiter in the intermediate elliptical orbit, the orbiter and tug together do not transfer into the 100 nm parking orbit but rather deboost into the atmosphere from the apogee of the intermediate orbit. Deboosting from that point results in considerable orbiter $\Delta V$ savings which permit a larger intermediate orbit and consequently lower tug $\Delta V$ and attendant increased payload.

Appendix 2 describes the $\Delta V$ savings resulting from deboosting from apogee of an elliptical parking orbit in more detail. The results are based on deorbiting from apogee of an elliptical orbit having a 100 nm perigee altitude. In all instances the deorbiting trajectories are selected in such a manner that the vehicle will enter the atmosphere at 400,000 ft with a flight path angle of 1.5 degrees. This flight path angle was selected to be the same as would be obtained from entering from a 100 nm circular orbit with a 500 ft/sec deboost $\Delta V$. Figure 5 shows the deorbit $\Delta V$ versus apogee altitude. The curve starts at an apogee altitude of 100 nm corresponding to a 100 mm circular orbit and extends all the way past synchronous altitude. The remarkable result of this curve is that the deboost $\Delta V$ that is 500 ft/sec for the 100 nm circular orbit decreases to 240 ft/sec, or less than one half, when deboosting from the apogee of a 100 x 150 nm orbit, and less than 80 for a 100 x 1000 nm orbit. The advantage of this lower deboost $\Delta V$ is offset by a higher entry velocity. A corresponding plot of entry velocity versus apogee altitude is shown on Figure 6. For apogee $\Delta V$ altitudes below 1000 nm the increase in entry velocity is relatively small.

For a further comparison, Figure 7 is presented on which the $\Delta V$ required to go into an intermediate elliptical orbit is added to the $\Delta V$ required to deorbit. The sum of the two $\Delta V$'s is equal to 500 ft/sec for an apogee altitude of 100 nm (corresponding to the 100 nm circular orbit). As the apogee is increased, the additional expenditure to go to an elliptical orbit is initially smaller than the saving obtained by deorbiting from a higher altitude and therefore the total $\Delta V$ is smaller. It reaches a minimum for an altitude of about 160 nm at which point the total is about 340 ft/sec. If the apogee altitude is further increased, the $\Delta V$ to get into the intermediate elliptical orbit increases faster than the $\Delta V$ to later deboost is decreased, and there is a net increase in the total $\Delta V$. It again reaches about 500 ft/sec at an apogee altitude of about 315 nm.

Although the above results were computed for the return of a tug and orbiter together, it is expected that the shuttle orbiter itself could save $\Delta V$ by deboosting from the apogee of an elliptical parking orbit.

## ANALYSIS

The one way payload to synchronous orbit was computed for the three modes just described and compared to the payload obtainable in the case where the on orbit propellant is not utilized. The calculations are based on the formulae derived in Appendix 3 "Reusable Tug - One Way Payload to a Higher Orbit for Given Total Initial Weight." The following assumptions apply:

| | | | |
|---|---|---|---|
| 1. | Orbiter: | Burnout weight | 329172 lb |
| | | On Orbit Propellant | 19084 lb |
| | | $I_{sp}$ | 458 sec |
| 2. | Tug: | Total Weight Including Payload | 65000 lb |
| | | Empty Weight to vary in such a manner that propellant fraction $\lambda = 0.88$ in each case. | |
| | | $I_{sp}$ | 460 sec |

3. Departure from a 100 nm easterly orbit (28.5 deg inclination) to a synchronous equatorial orbit.

4. Plane change to equatorial orbit is executed at apogee of large Hohman transfer.

5. Gravity loss of 60 ft/sec for tug* and 10% of burn for on orbit propellant utilization.

6. Orbiter enters atmosphere at 400,000 ft altitude at a flight path angle of 1.5 degrees.

The results are shown on the Table below.

| | No Onboard Propellant Utilization | Intermediate Circular Orbit | Intermediate Elliptical Orbit | Intermediate Elliptical Orbit With Deboost From Apogee |
|---|---|---|---|---|
| One Way Payload to Synchronous Orbit | 6778 | 7375 | 7764 | 9787 |
| Empty Tug Weight ($\lambda$ = 0.88) | 6987 | 6917 | 6869 | 6628 |
| Intermediate Orbit Size nm | D.N.A | 166 circ | 100 x 231 | 100 x 530 |
| One Way $\Delta V$ to be Delivered by Tug | 14163 | 14021 | 13929 | 13440 |

When no onboard propellant is utilized, the payload is almost 6800 lb (first column of Table 1). This payload increases to almost 7400 lb when the orbiter on orbit propellant is utilized to bring the orbiter and the tug to an intermediate circular orbit of 166 nm. This utilization of the orbiter on orbit propellant decreases the one way $\Delta V$ to be delivered by the tug by about 140 ft/sec. (see bottom row of Table 1).

As mentioned earlier going into an intermediate circular orbit requires a greater $\Delta V$ than when the intermediate orbit is elliptical. Column 3 shows the result of this calculation. The one way payload is almost 7800 lb, an increase of about 400 lb over the case of an intermediate circular orbit,

*"Finite-Thrust Transfers to Synchronous Orbit and Translunar Injection," A. L. Schreiber, Bellcomm Memorandum for File, September 4, 1968.

and it is brought about by savings in one way $\Delta V$ of about 100 ft/sec. The intermediate elliptical orbit is 100 x 231 nm.

The results of deboosting the orbiter and tug together from apogee of the intermediate orbit is given on column 4. A further gain in payload of 2000 lb is realized, resulting in a total payload of almost 9800 lb or an increase of 44% from the original value of 6800 lb. The savings in deboost $\Delta V$ permit increasing the size of the intermediate elliptical orbit of 100 x 530 nm and the additional savings in required one way tug $\Delta V$ from the previous case is 490 ft/sec. This large additional saving results partly because less $\Delta V$ is required to deboost, and partly because no $\Delta V$ is expended to return from the intermediate orbit to the parking orbit.

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## APPENDIX 1

### $\Delta$V-LOSS FOR INTERMEDIATE CIRCULAR PARKING ORBIT

Given a spacecraft in a circular parking orbit of radius $R_1$ that goes into a larger coplanar circular orbit of radius $R_3$, the $\Delta V$ losses incurred by going first into an intermediate circular orbit of radius $R_2$ are computed. The following nomenclature was used:

| | |
|---|---|
| $R$ | Radius (ft) |
| $V_{a_{i,j}}$ | Velocity at apoapsis of an ellipse having periapsis radius $R_i$ and apoapsis radius $R_j$ (ft/sec) |
| $V_{c_i}$ | Circular velocity at radius $R_i$ (ft/sec) |
| $V_{p_{i,j}}$ | Velocity at periapsis of an ellipse having periapsis radius $R_i$ and apoapsis radius $R_j$ (ft/sec) |
| $\mu$ | Gravitational constant (ft$^3$/sec$^2$) |
| $\Delta V_{i-j}$ | $\Delta V$ expenditure to go from a circular orbit of radius $R_i$ to a larger circular orbit of radius $R_j$ with a Hohman transfer. |
| $\Delta$ | $\Delta V$ loss due to going to an intermediate circular orbit. |

Subscripts (refer to)

| | |
|---|---|
| 1 | Smallest parking orbit. |
| 2 | Intermediate orbit. |
| 3 | Large orbit. |

The $\Delta V$ requirement for a Hohman transfer from a circular orbit of radius $R_1$ to a radius $R_2$ is

$$\Delta V_{1-2} = (V_{p_{1,2}} - V_{c_1}) + (V_{c_2} - V_{a_{1,2}}) \qquad (1)$$

In a similar manner to go from radius $R_2$ to radius $R_3$

$$\Delta V_{2-3} = (V_{p_{2,3}} - V_{c_2}) + (V_{c_3} - V_{a_{2,3}}) \tag{2}$$

and from radius $R_1$ directly to radius $R_3$

$$\Delta V_{1-3} = (V_{p_{1,3}} - V_{c_1}) + (V_{c_3} - V_{a_{1,3}}) \tag{3}$$

Therefore the actual loss incurred by going to an intermediate parking orbit is

$$\Delta = \Delta V_{1-2} + \Delta V_{2-3} - \Delta V_{1-3} \tag{4}$$

or by substituting (1), (2), and (3) in (4) and simplifying

$$\Delta = V_{p_{1,2}} - V_{a_{1,2}} + V_{p_{2,3}} - V_{a_{2,3}} - V_{p_{1,3}} + V_{a_{1,3}} \tag{5}$$

For an ellipse with a periapsis radius $R_i$ and an apoapsis radius $R_j$ the velocity at periapsis is

$$V_{p_{i,j}} = \sqrt{\left(\frac{2\mu}{R_i+R_j}\right)\left(\frac{R_j}{R_i}\right)}$$

and the velocity at apoapsis

$$V_{a_{i,j}} = \sqrt{\left(\frac{2\mu}{R_i+R_j}\right)\left(\frac{R_i}{R_j}\right)}$$

and substituting the appropriate expressions in (5)

$$\Delta = \sqrt{\left(\frac{2\mu}{R_1+R_2}\right)\left(\frac{R_2}{R_1}\right)} - \sqrt{\left(\frac{2\mu}{R_1+R_2}\right)\left(\frac{R_1}{R_2}\right)} + \sqrt{\left(\frac{2\mu}{R_2+R_3}\right)\left(\frac{R_3}{R_2}\right)} - \sqrt{\left(\frac{2\mu}{R_2+R_3}\right)\left(\frac{R_2}{R_3}\right)} - \sqrt{\left(\frac{2\mu}{R_1+R_3}\right)\left(\frac{R_3}{R_1}\right)} + \sqrt{\left(\frac{2\mu}{R_1+R_3}\right)\left(\frac{R_1}{R_3}\right)}$$

The quantity, $\Delta$, the $\Delta V$ loss due to going to an intermediate circular orbit, is plotted on Figure 4 vs the altitude of the intermediate orbit for various final orbit altitudes as parameter. The curves are plotted on log-log paper starting vertically at a $\Delta V$ value of 10 ft/sec and an altitude of 100 nm. The plot assumes the lower altitude to be always 100 nm. For a final altitude below 1500 nm, the $\Delta V$ loss for going into a lower intermediate altitude becomes negligible.

## APPENDIX 2

## Deorbit $\Delta V$ from Apoapsis of an Elliptical Parking Orbit

The following nomenclature was used:

| | |
|---|---|
| $R$ | Radius (ft) |
| $V$ | Velocity (ft/sec) |
| $\gamma$ | Flight path angle (degree) |
| $\mu$ | Gravitational constant ($ft^3/sec^2$) |
| $\Delta V_{deorbit}$ | Velocity impulse required to deorbit from apoapsis (ft/sec) |
| $\Delta V_e$ | Velocity impulse required to go into an ellipse (ft/sec) |
| $\Delta V_t$ | Total $\Delta V$ to go into an elliptical orbit and deorbit from apogee (ft/sec) |

Subscripts refer to:

| | |
|---|---|
| a | Apoapsis |
| c | circular |
| e | Entry Condition |
| p | periapsis |

On an ellipse having $R_p$ and $R_a$ as periapsis and apoapsis radii respectively, the apoapsis velocity is

$$V_a = \sqrt{\left(\frac{2\mu}{R_a + R_p}\right)\left(\frac{R_p}{R_a}\right)} \qquad (1)$$

For deorbiting from this ellipse and entering the atmosphere at a given radius and flight path angle, a slightly different velocity at apoapsis is required. Let $V_a'$ be this velocity; then

$$\Delta V_{deorbit} = V_a - V_a' \qquad (2)$$

The deorbiting vehicle follows an ellipse having an apoapsis radius $R_a$, an unknown apoapsis velocity $V_a'$, an entry radius $r_e$, an entry flight path angle $\gamma_e$ and an unknown entry velocity $V_e$. Equating both energy and angular momentum at apoapsis and entry radius provides

$$V_e^2 - \frac{2\mu}{R_e} = V_a'^2 - \frac{2\mu}{R_a} \tag{3}$$

and

$$R_a V_a' = R_e V_e \cos\gamma_e \tag{4}$$

from (4)

$$V_a' = \left(\frac{R_e}{R_a}\right) V_e \cos\gamma_e$$

which substituted in (3) provides

$$V_e = \sqrt{\frac{2\mu\left(\frac{1}{R_e} - \frac{1}{R_a}\right)}{1 - \left(\frac{R_e}{R_a}\right)^2 \cos^2\gamma_e}}$$

and

$$V_a' = \left(\frac{R_e}{R_a}\right) \cos\gamma_e \sqrt{\frac{2\mu\left(\frac{1}{R_e} - \frac{1}{R_a}\right)}{1 - \left(\frac{R_e}{R_a}\right)^2 \cos^2\gamma_e}}$$

It follows that the deorbiting $\Delta V$ is

$$\Delta V_{deorbit} = \sqrt{\left(\frac{2\mu}{R_p + R_a}\right)\left(\frac{R_p}{R_a}\right)} - \left(\frac{R_e}{R_a}\right) \cos\gamma_e \sqrt{\frac{2\mu\left(\frac{1}{R_e} - \frac{1}{R_a}\right)}{1 - \left(\frac{R_e}{R_a}\right)^2 \cos^2\gamma_e}}$$

$\Delta V$ deorbit is plotted versus apogee altitude on Figure 5. Perigee altitude is 100 nm in all cases. Entry altitude is 400,000 ft at a flight path angle of 1.5 degrees. For a circular orbit of 100 nm, the deorbit $\Delta V$ is 500 ft/sec. Going into an ellipse, this value decreases rapidly with increasing apogee altitude. It is less than half the circular orbit value at an apogee altitude of 150 nm, and less than 100 ft/sec at an apogee altitude of 1000 nm.

For a constant flight path angle and altitude at the entry point, the entry velocity increases with apoapsis altitude. A plot of entry velocity is shown on Figure 6. At low altitudes the increase in entry velocity is relatively modest.

Now considered is the case of a space vehicle that is initially in a 100 nm circular parking orbit and then injected into an elliptical parking orbit and finally de-orbited from apoapsis of this ellipse. Let $V_p$ be the velocity at periapsis and $V_c$ the initial circular velocity; the $\Delta V$ required to go into an ellipse of apoapsis radius $R_a$ is

$$\Delta V_e = V_p - V_c = \sqrt{\left(\frac{2\mu}{R_p + R_a}\right)\left(\frac{R_a}{R_p}\right)} - \sqrt{\frac{\mu}{R_p}}$$

and the total requirement to first go into an ellipse and then deorbit is

$$\Delta V_t = \Delta V_e + \Delta V_{deorbit}$$

Figure 7 shows a plot of this sum versus apogee altitude when departing from a 100 nm altitude circular orbit and entering the atmosphere at 400,000 ft with a flight path angle of 1.5 degree.

For the extreme case of the 100 nm circular orbit, this sum equals 500 ft/sec. For increasing apogee radius the $\Delta V$ deorbit initially decreases more rapidly then the $\Delta V$ required to go into an elliptical orbit increases. Therefore $\Delta V_t$ is less than 500 ft/sec, and it reaches a minimum at an altitude of about 160 nm. It increases slowly thereafter and again reaches 500 ft/sec at an altitude of 315 nm. Two conclusions may be drawn from these curves:

a. If a slight increase in entry velocity is acceptable, it is more economical to inject a spacecraft into a slightly elliptical orbit and deorbit from apogee instead of deorbiting directly from the circular orbit.

b. If a vehicle is in an elliptical orbit, considerable savings may be realized by deorbiting it directly from apogee rather than first going into a circular orbit and deorbiting from the circular orbit.

## APPENDIX 3

### Reusable Tug - One Way Payload to a Higher Orbit For Given Total Initial Tug Weight

Given a space tug of given initial weight in earth orbit, the one way payload delivered to a higher orbit is computed as a function of propellant mass fraction $\lambda$, specific impulse $I_{sp}$, and both transfer and return $\Delta V$. The following nomenclature is used throughout:

| | |
|---|---|
| $A = e^{\Delta V_1/g\ I_{sp}}$ | Vehicle weight ratio required for Hohman transfer to higher orbit (-) |
| $B = e^{\Delta V_2/g\ I_{sp}}$ | Vehicle weight ratio required for Hohman transfer to return to lower orbit (-) |
| $P_1$ | Propellant required to go to higher orbit (lb) |
| $P_2$ | Propellant required to return to lower orbit (lb) |
| PL | Payload to be brought to higher orbit if tug returns empty (lb) |
| S | Weight of empty tug (lb) |
| $W_t$ | Total initial weight of tug (lb) |
| $\lambda$ | Initial propellant fraction of tug (-) |
| $\Delta V_1$ | Velocity increment required for Hohman transfer to higher orbit (ft/sec) |
| $\Delta V_2$ | Velocity increment required for Hohman transfer to lower orbit (ft/sec) |

The weight ratio for the trip to the higher orbit provides

$$A = \frac{S + P_2 + PL + P_1}{S + P_2 + PL} \tag{1}$$

and for the return trip to the low orbit (the payload remains in the higher orbit):

$$B = \frac{S + P_2}{S} \tag{2}$$

The propellant fraction $\lambda$ is by definition

$$\lambda = \frac{P_1 + P_2}{P_1 + P_2 + S} \tag{3}$$

furthermore the total weight is

$$W_t = P_1 + P_2 + S + PL \tag{4}$$

These four equations (1), (2), (3), and (4) can be transformed appropriately to give the four unknown quantities $P_1$, $P_2$, PL, and S.

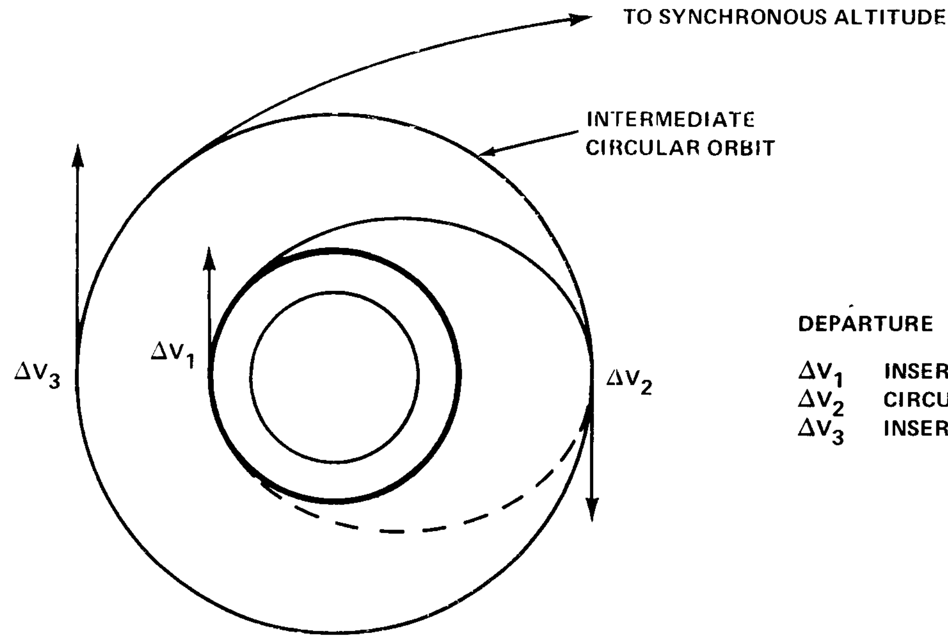
$$PL = W_t \quad \frac{[\lambda/(\lambda-1)] + 1 - AB}{\{[\lambda/(\lambda-1)] + 1 - B\}A}$$

$$S = \frac{(A-1)PL}{[\lambda/(1-\lambda)] + 1 - AB}$$

$$P_2 = S(B-1)$$

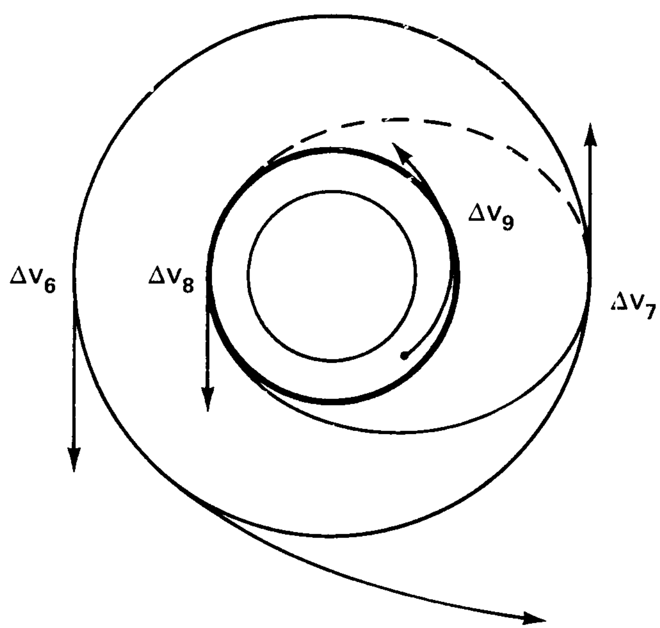
$$P_1 = (S + P_2 + PL)\ (A-1)$$

A graphical representation of these equations is given on Figure 8 for the case of $\lambda = 0.88$ and A = B. The four quantities $P_1/W_t$, $P_2/W_t$, $S/W_t$, and $PL/W_t$ plotted vs A within range 2 to 2.8 which for a $I_{sp} = 460$ sec corresponds to a range of a one way $\Delta V$ of 10,000 to 15,000 ft/sec.




DEPARTURE

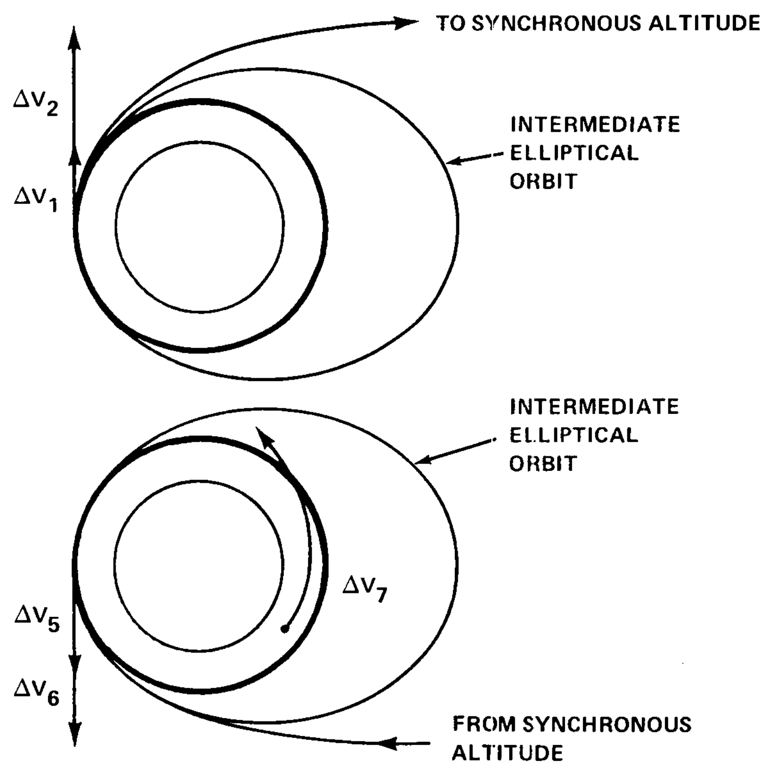
$\Delta V_1$ INSERT INTO INTERMEDIATE TRANSFER ORBIT
$\Delta V_2$ CIRCULARIZE AT APOGEE TO INTERMEDIATE CIRCULAR ORBIT
$\Delta V_3$ INSERT INTO TRANSFER ORBIT TO REACH SYNCH ALT.




RETURN

$\Delta V_6$ CIRCULARIZE AT PERIGEE INTO INTERMEDIATE CIRCULAR ORBIT
$\Delta V_7$ RETRO INTO INTERMEDIATE TRANSFER ORBIT
$\Delta V_8$ CIRCULARIZE AT PERIGEE INTO PARKING ORBIT
$\Delta V_9$ DE-ORBIT FOR ENTRY

FIGURE 1 - USE OF ON ORBIT PROPELLANT TO GO INTO AN INTERMEDIATE CIRCULAR ORBIT




DEPARTURE

$\Delta V_1$ INSERT INTO INTERMEDIATE ELLIPTICAL ORBIT
$\Delta V_2$ AFTER ONE REVOLUTION ALONG ELLIPSE INSERT INTO TRANSFER ORBIT TO REACH SYNCHRONOUS ALTITUDE

RETURN

$\Delta V_5$ DEBOOST AT PERIGEE INTO INTERMEDIATE ELLIPTICAL ORBIT
$\Delta V_6$ CIRCULARIZE AT PERIGEE AFTER ONE REVOLUTION
$\Delta V_7$ DE-ORBIT FOR ENTRY

FIGURE 2 - USE OF ON ORBIT PROPELLANT TO GO INTO AN INTERMEDIATE ELLIPTICAL PARKING ORBIT

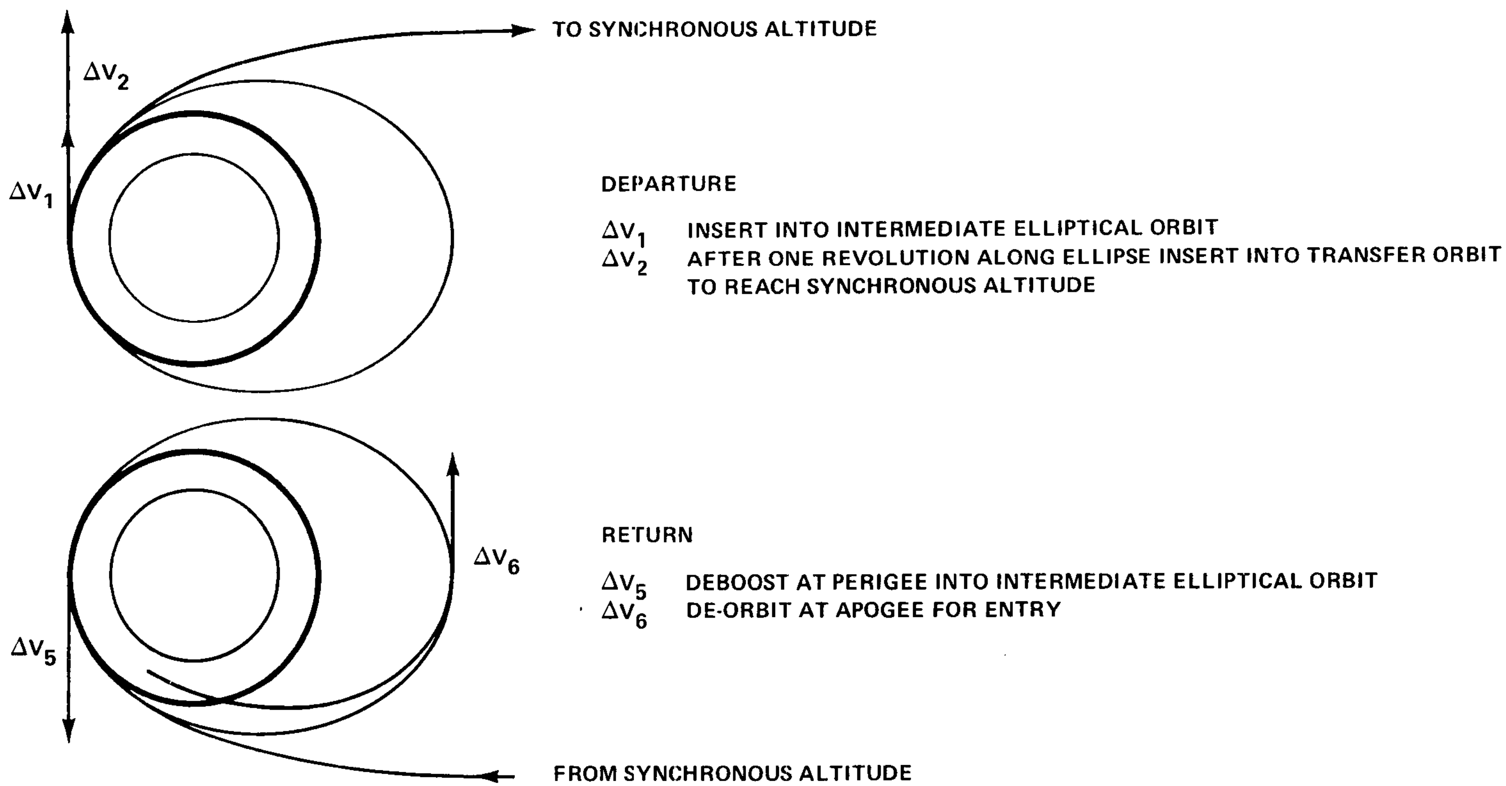



FIGURE 3 - USE OF ON ORBIT PROPELLANT TO GO INTO AN INTERMEDIATE ELLIPTICAL PARKING ORBIT AND DE-ORBIT FROM APOGEE

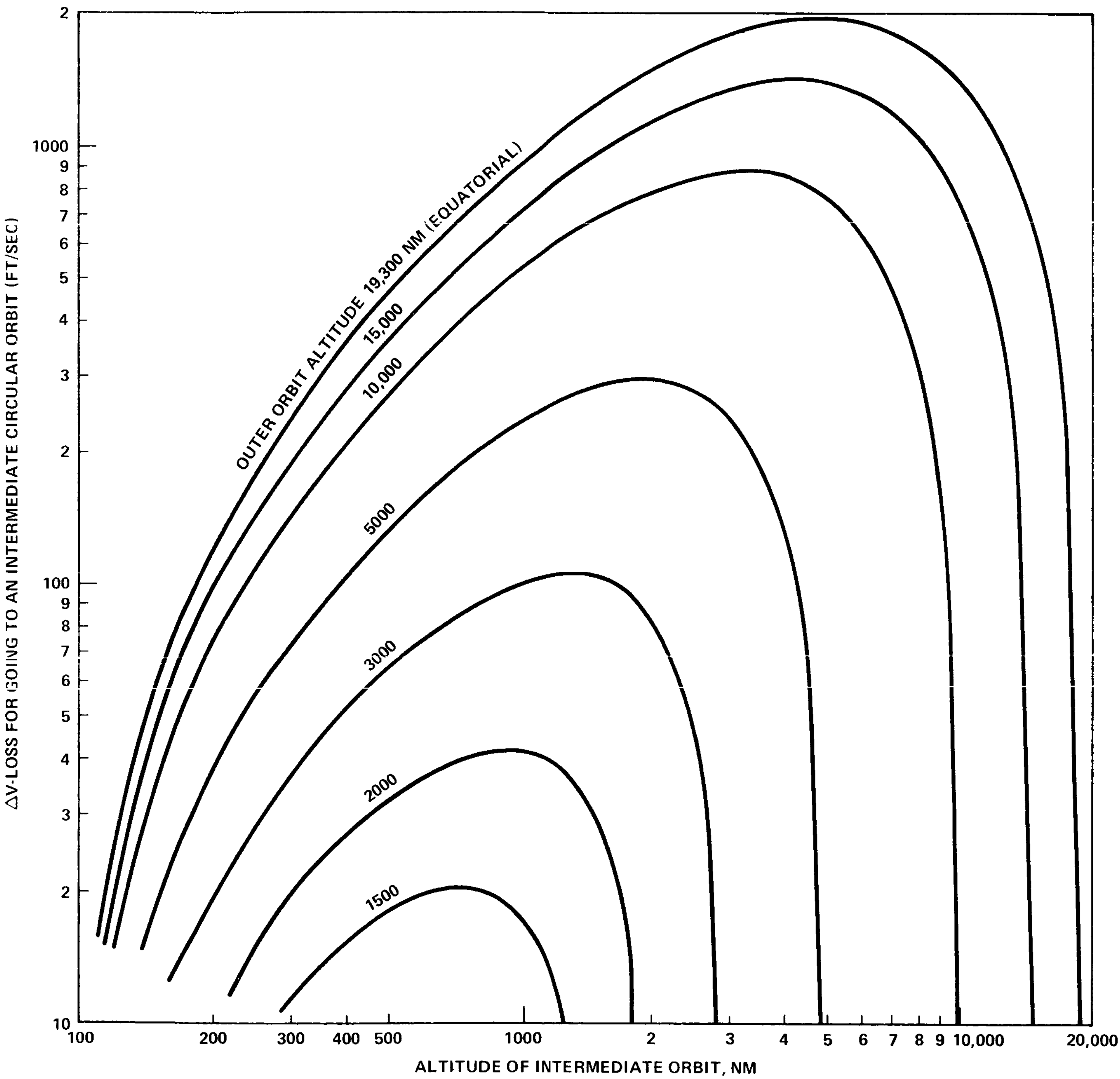



FIGURE 4 - ΔV PENALTY FOR GOING TO AN INTERMEDIATE CIRCULAR ORBIT

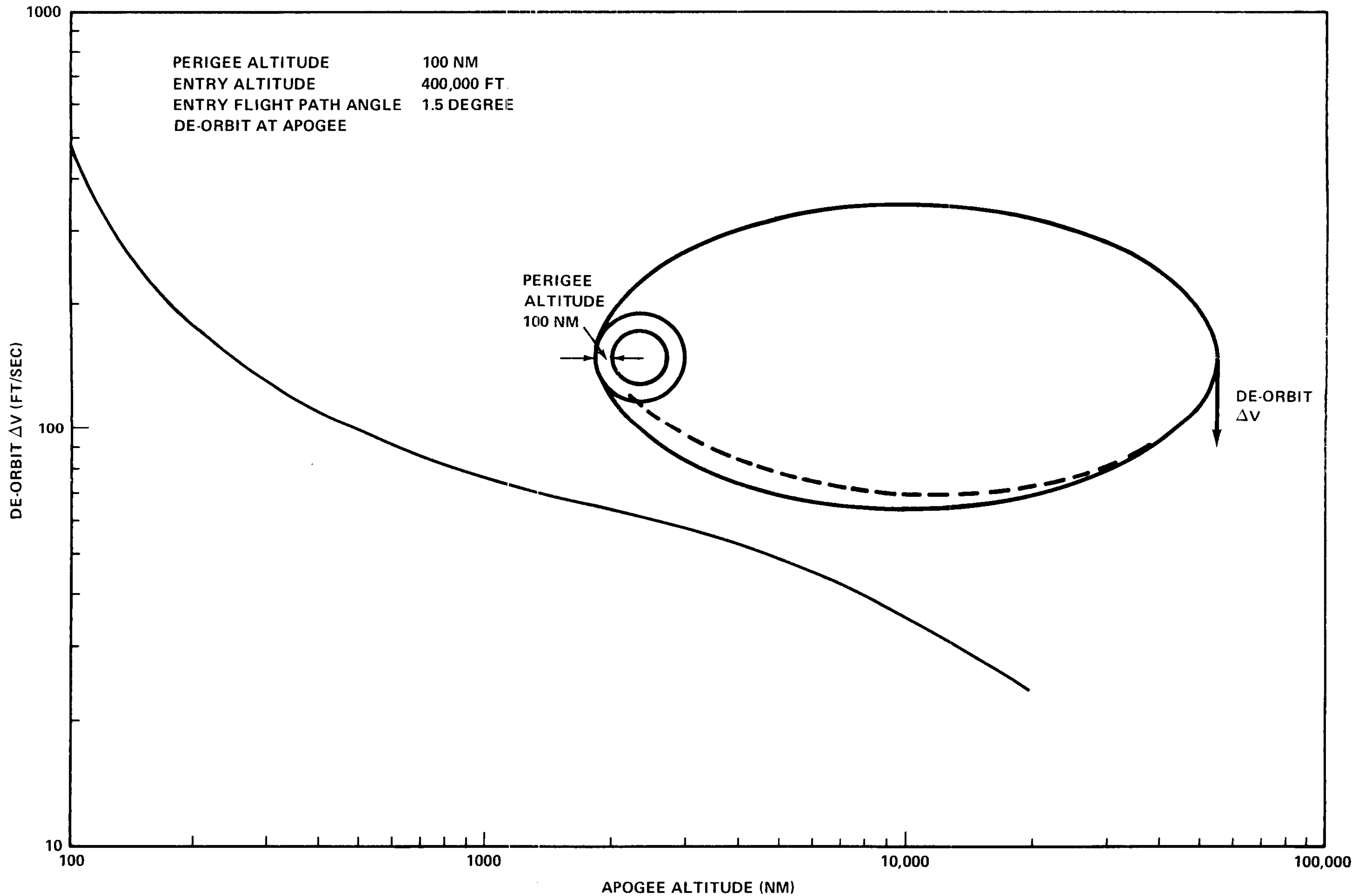



FIGURE 5 - DE-ORBIT ΔV FROM AN ELLIPTICAL ORBIT VS APOGEE ALTITUDE

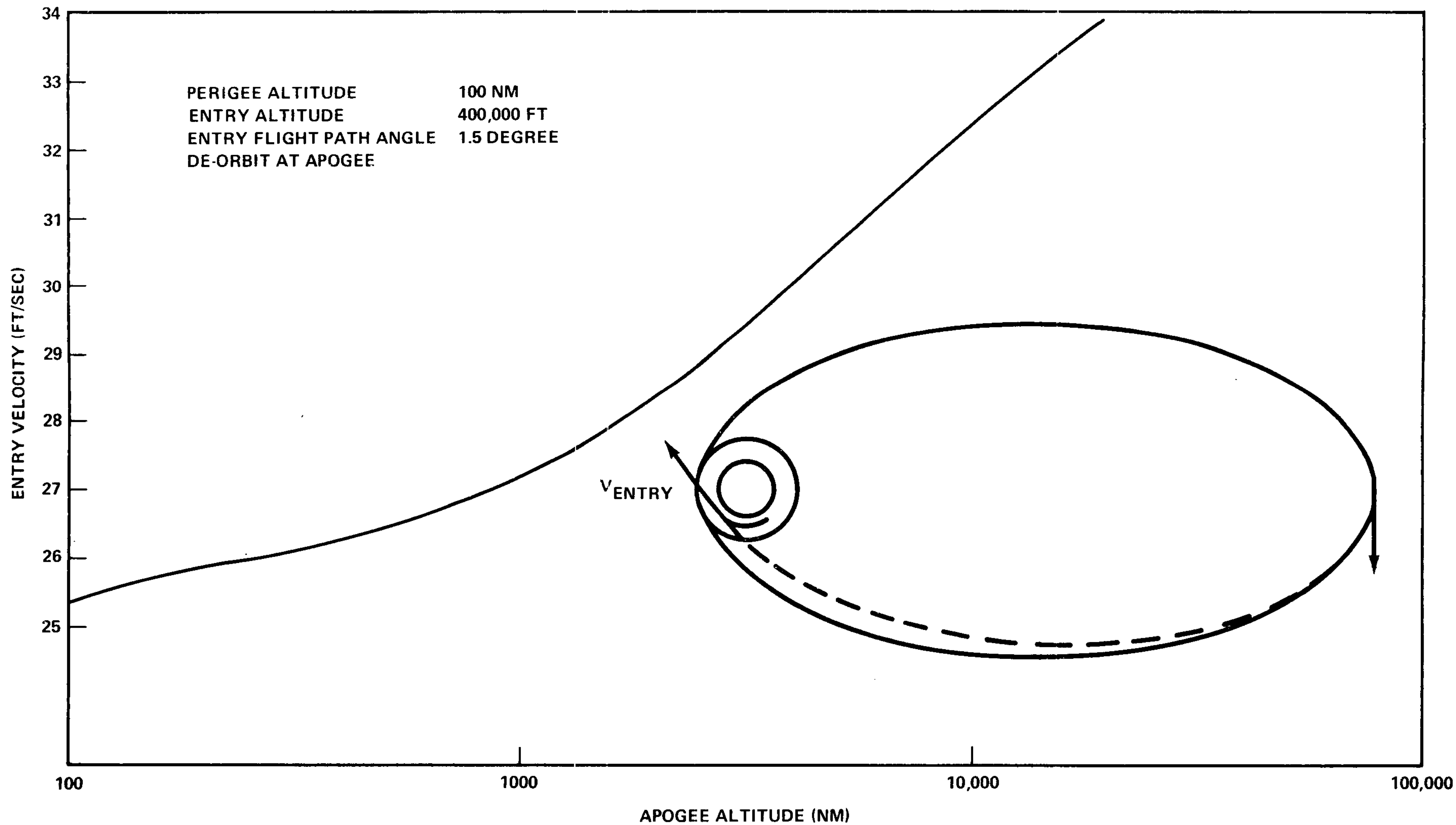



FIGURE 6 - ENTRY VELOCITY WHEN DE-ORBITING FROM ELLIPTICAL ORBIT VS APOGEE ALTITUDE

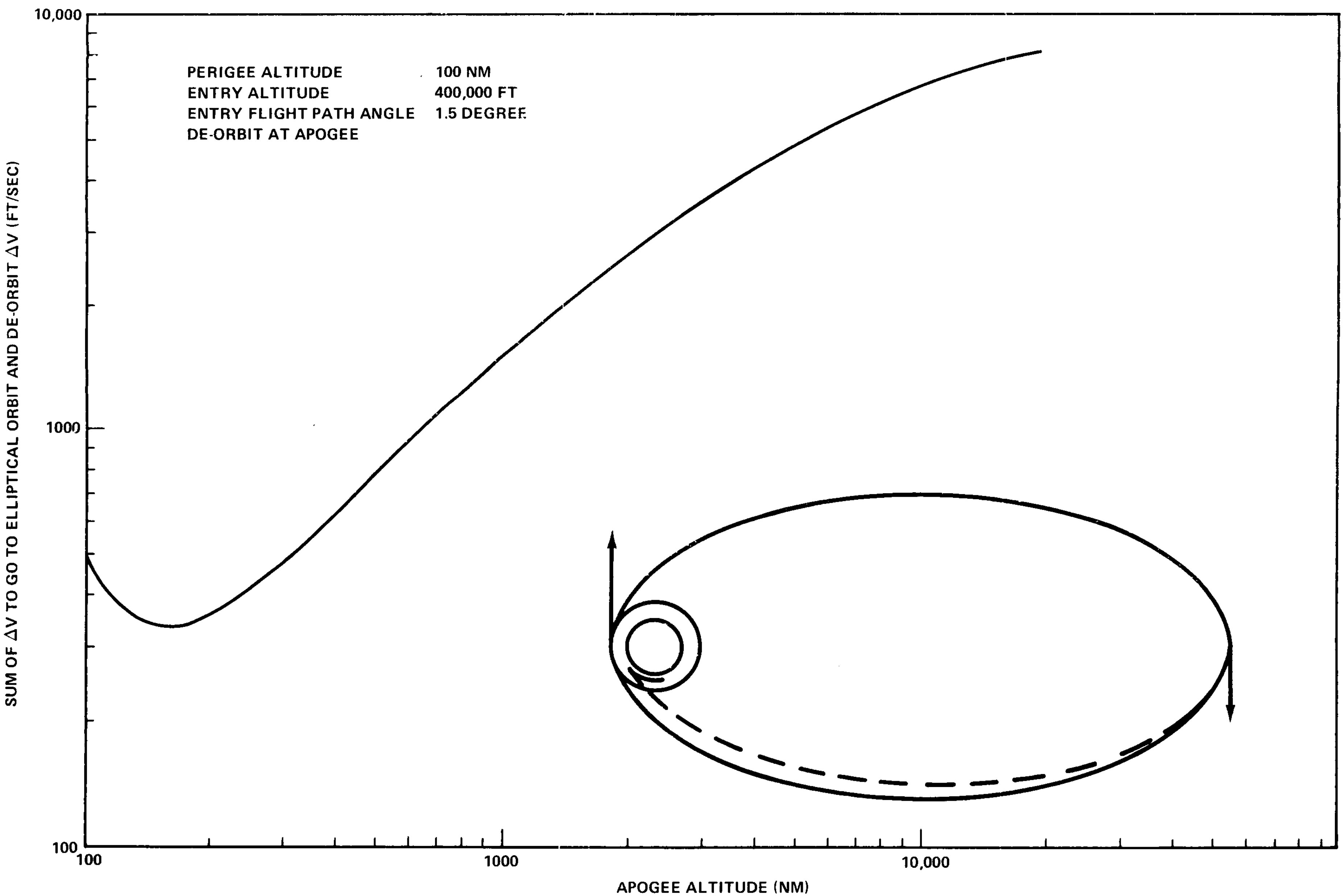



FIGURE 7 - SUM OF ΔV TO GO TO ELLIPTICAL ORBIT AND DE-ORBIT ΔV VS APOGEE ALTITUDE

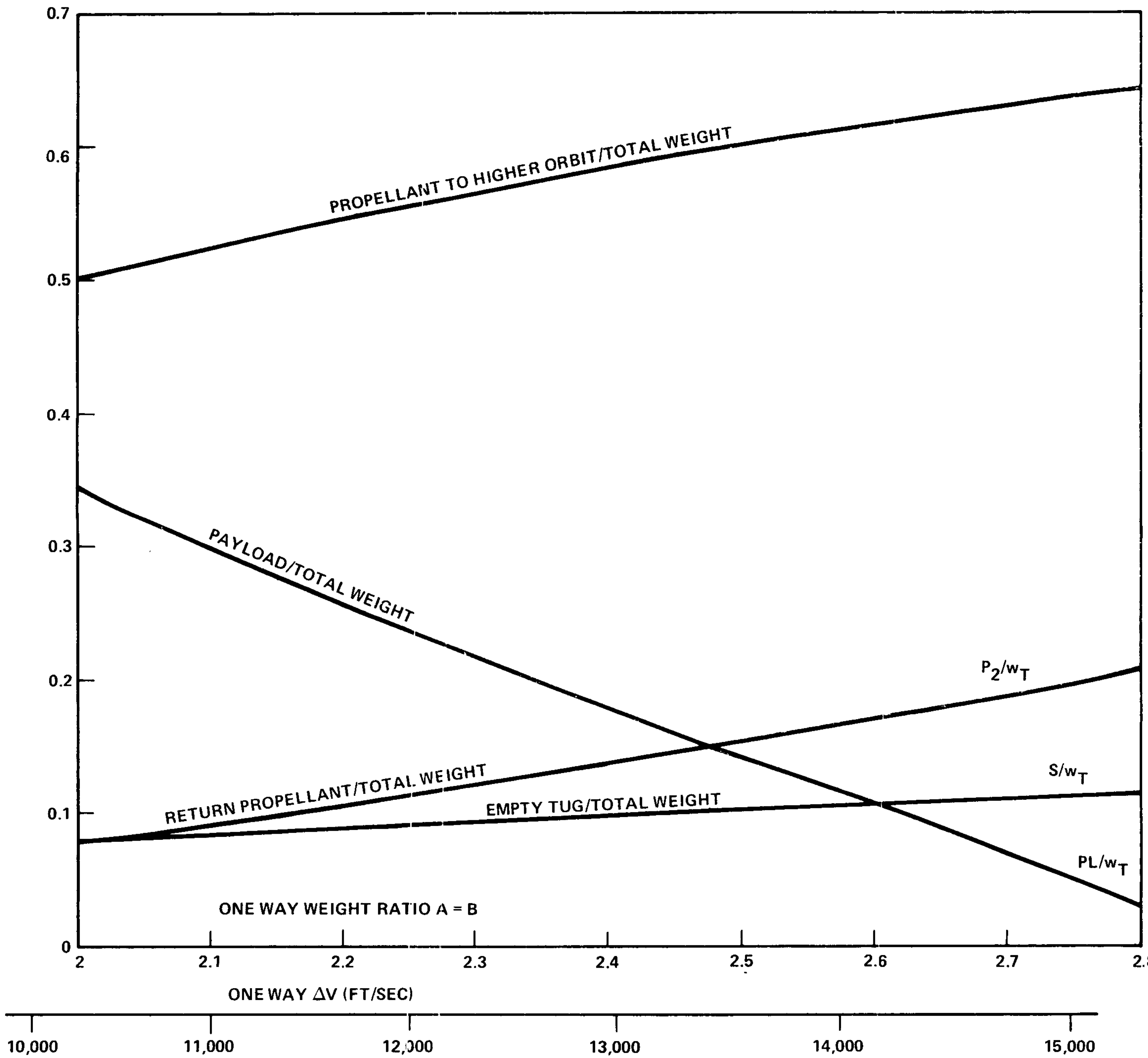

PROPELLANT TO HIGHER ORBIT/TOTAL WEIGHT
PAYLOAD/TOTAL WEIGHT
RETURN PROPELLANT/TOTAL WEIGHT
EMPTY TUG/TOTAL WEIGHT
P2/wT
S/wT
PL/wT
ONE WAY WEIGHT RATIO A = B
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
ONE WAY ΔV (FT/SEC)
10,000
11,000
12,000
13,000
14,000
15,000

FIGURE 8

Subject: Use of On-Orbit Propellant in Shuttle Orbiter for Tug Payload Increase - Case 237

From: J. J. Schoch

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